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Assessing the environmental impacts of production- and consumption-side measures in sustainable agriculture intensification in the European Union

Anna Liza Bais-Moleman[a,*], Catharina J.E. Schulp[a], Peter H. Verburg[a,b]

[a] Department of Environmental Geography, Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, De Boelelaan 1087, 1081 HV Amsterdam, the Netherlands

[b] Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Birmensdorf, Switzerland

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ABSTRACT

Sustainable agricultural intensification (SI) is an important strategy to respond to the combined challenge of achieving food security and providing public goods and ecosystem services to society, including mitigation and adaptation of climate change. Sustainable intensification includes a wide range of measures at both the supply and demand-side of agricultural production. However, currently, it is unclear what are the most effective and priority measures. This study assesses the potential of different SI measures for reducing GHG (greenhouse gas) emissions and increasing land use efficiency in the European Union's agriculture sector. A scenario approach was combined with life cycle analysis to quantify the environmental impacts of a number of different SI measures. The sustainable intensification measures assessed in this study are: 1) changing human diet; 2) using food waste in livestock diets; 3) shifting from monoculture cropping to crop rotation, and, 4) incorporating crop residues into the soil. The results reveal that the studied SI measures have the potential to increase land use savings, ranging from 0.06 to 3.32 m^2/person/day, while GHG emission savings ranging from 71 to 1872 g CO_2-eq/person/day can be achieved at EU level. Among these SI measures, changing human diet showed a remarkably high reduction of environmental impacts. On the contrary, increased GHG emission savings in the other SI measures (i.e. crop residue incorporation in the field and replacing soybean meal in conventional feed by food waste-based feed) are counter effected by increased GHG emissions in the energy sector due to reduction of feedstock availability for bioenergy production. The approach used in this study allows the assessment of both the production and consumption-side SI measures and allows the identification of the most effective SI measures and their potential trade-offs.

1. Introduction

Global biomass demand for food, fiber and fuel is expected to increase considerably in the near future as a result of growing population, dietary preferences shifting towards the intake of more animal products, and increasing biofuel demand driven by bioenergy policies such as the US renewable fuel standard and the European Union's (EU's) renewable energy directive (European Parliament, 2009; U.S. Congress, 2005; European Parliament, 2003). Increasing demands for food and biofuels are likely to increase GHG emissions from agriculture due to increasing fertilizer input for cropland intensification or due to the loss of carbon stocks as a consequence of cropland expansion and associated deforestation or conversion of permanent grasslands.

The EU is no exception to this. The EU's agricultural production is among the most intensive in the world. The high productivity in Europe is based on intensification of land-based production by high agricultural inputs like fertilizers, pesticides and mechanical energy (Erb et al., 2008) which is responsible for various negative environmental impacts such as increased GHG emissions (with EU's agriculture contributing about 10% of total anthropogenic GHG emissions; EuroStat, 2017), soil acidification, eutrophication and reduction of agro-biodiversity (Kleijn et al., 2009). Preventing or minimizing environmental degradation is an important and urgent sustainability challenge of the coming decades. Sustainable agricultural intensification (SI) is frequently mentioned as a potential solution to increase production of food, fiber and energy to meet growing demands without converting high carbon stock land (Royal Society, 2009; Rockström et al., 2017). Many studies related to SI focused on estimating the opportunities of increasing production through agronomic SI measures, such as changing cropping system by application of straw mulching, crop rotation, and intercropping (Drury

* Corresponding author.
E-mail address: annaliza.bais-moleman@vu.nl (A.L. Bais-Moleman).

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et al., 2008; Lehtinen et al., 2014; Qin et al., 2015; Reckling et al., 2014, 2016; Weltin et al., 2018).

We define SI beyond the simple definition of "more output on the same land area while reducing adverse environmental impacts and preventing the expansion of agricultural land" (Royal Society, 2009). Instead, we adopt the definition of Rockström et al. (2017), who state that SI is about "adopting practices along the entire value chain of the global food system that meet rising needs for nutritious and healthy food through practices that build social-ecological resilience and enhance natural capital (e.g. soil, biodiversity, nutrients, water, etc.) within the safe operating space of the Earth system". Intensification is associated with increasing use of resources in the most efficient way possible, i.e. with simultaneous increase in both resource use and resource use efficiency (Struik and Kuyper, 2017). Based on this definition, besides on agronomic measures, sustainable intensification should also consider strategies such as reduction of the footprint of human and livestock diets, reducing food waste, and other strategies to improve the efficiency of food systems (Scherer and Verburg, 2017; Weltin et al., 2018).

In the last few decades, intensive agricultural management practices in European agriculture have resulted in soil degradation, e.g. loss of soil organic carbon (Virto et al., 2015; Lal, 2002). About 45% of the European soils exhibit low organic matter contents which is considered one of the major threats to soils (Rusco et al., 2001). Therefore, SI measures aimed at increasing soil organic carbon have high potential in the European context, with potential synergies of carbon storage and agricultural production benefits (Pretty and Bharucha, 2014; Lal, 2018). Double or multiple cropping systems and soil mulching could be among the measures to achieve SI in this context, but are, so far, hardly implemented in Europe (Thomsen and Christensen, 2004; Lehtinen et al., 2014; Reckling et al., 2016; Prestele et al., 2018).

Given the large contribution of livestock production to anthropogenic GHG emissions (Gerber et al., 2013), alternative management options for the livestock system are an important component of SI. Europe's livestock system is also a C-intensive system wherein large amounts of animal feed ingredients are imported from outside Europe (FEFAC, 2015; Oil World, 2008) contributing to land use change in exporting countries (Achard et al., 2002) and entailing transport over long distances, resulting in adverse environmental impacts (Eriksson et al., 2005). One of the principal strategies to reduce the environmental impact of livestock is by changing animal diet to low-impact alternatives. Combining this with reducing the EU's food waste disposal is considered an attractive option. The EU is producing about 89–100 Mt food waste annually (European Commission, 2010). Recycling of food waste for animal feed is actively promoted in Asia, e.g. Japan, Taiwan, Thailand and South Korea (Menikpura et al., 2013) but it is not widely accepted for feed production in the EU. Utilizing food waste for animal feed will both reduce environmental impacts of food waste disposal and animal feed production as well as increase the efficiency of agricultural biomass by cascading use, i.e. the use of biomass first for higher added-value products such as food, encouraging recycling afterwards and energy recovery at their end-of-life (Bais-Moleman et al., 2018; Keegan et al., 2013).

On the consumer side, there is widespread evidence that dietary composition strongly influences GHG emissions from agriculture (Tilman and Clark, 2014) and several studies suggested a change to vegetarian or vegan diets to reduce anthropogenic GHG emissions (van Dooren et al., 2014; Scarborough et al., 2014). However, complete removal of meat and dairy products in human diet may be difficult to achieve in the short term.

As current diets with high quantities of animal products may have negative health consequences, dietary guidelines have been issued by governments, health councils and nutrition institutes in many EU member states (FAO, 2017). Such guidelines, however, do not address environmental concerns related to food intake, such as its impact on natural environment and sustainability issues. Nevertheless, the synergy of recommended diets in terms of environmental benefits might be considerable, meaning that they may be regarded as a component of SI as argued by Scherer and Verburg (2017). Previous studies mainly focused their assessment at food commodity level and few studies calculated the benefits at national level (van Dooren et al., 2014; Scarborough et al., 2014; Meier and Christen, 2013). Moreover, studies on the impact of European diet change commonly base their calculations on extreme diets, e.g. full vegetarian or vegan diets (Scarborough et al., 2014) or Mediterranean dietary patterns (Saez-Almendros et al., 2013; Aboussaleh et al., 2017). However, these studies often disregard transport emissions of domestically produced and imported food commodities in their analysis, and effects on trade have not been systematically assessed.

While many SI measures are well known and studied (Reckling et al., 2014, 2016; Lehtinen et al., 2014; Alexander et al., 2016), there is still a lack of systematic quantification of their overall potential as well as trade-offs elsewhere in the value chain on reducing GHG emissions and increase land use efficiency at country and EU levels. This lack of systematic quantification makes it difficult to target which sustainable intensification measures are the most effective, and where. This study aims at comprehensively assessing and comparing the potential effects of the mentioned sustainable intensification measures on GHG emissions and land use in the EU's agriculture sector. Secondly, we aim at evaluating trade-offs with other climate mitigation strategies and effects of SI measures on domestic production, trade and yield gap. We focus in the EU member states (EU-28) and employ a scenario approach combined with life cycle analysis. The study focuses on biomass production and use (both production- and consumption-side SI measures) to assess the environmental impacts of both agricultural and food systems more effectively and comprehensively.

2. Materials and methods

We selected a set of production- and consumption-side SI measures along the value chain of the EU's agricultural and food systems and defined, for each measure a reference scenario and a SI scenario in which the measure was assumed to be fully implemented (Table 1). The measures assessed are considered to be part of SI because they represent practices along the food value chain that contribute in meeting the growing demand for nutritious and healthy food to support human well-being while enhancing the efficiency of natural resources and reducing the environmental impacts, which is supported by the SI definition provided by Rockström et al. (2017). The measures are also explicitly mentioned as part of the conceptual framework of SI (field of Actions I and II) (Weltin et al., 2018).

For each SI measure, differences in environmental impacts between the reference scenario and the SI scenario were quantified as the absolute differences in GHG emissions (g CO_2-eq/person/day, which is an adjusted indicator including CO_2, CH_4 and N_2O), and land use (m^2/person/day). A Life Cycle Assessment (LCA) was applied, conveniently employing the calculation tool from BioGrace (2014), IPCC (2006), FeedPrint (2015), to quantify the GHG emission savings of each SI measure. The description, life cycle inventory, system boundary, calculation of GHG emission savings and land use savings of each SI scenario are elaborated below. GHG emission- and land use savings were calculated at country level and aggregated to EU level. Calculations represent the situation in 2010.

2.1. SI1: changing human diets

2.1.1. Description, system boundary and life cycle inventory

Current human food intake in g/person/day for each food commodity at country level (Table A1 in Appendix A) was adopted from FAOSTAT food balances in 2010 (FAOSTAT, 2010), taking into account food losses and wastes in the supply chain (FAO, 2011). Food intake was calculated following:

Table 1
List of SI pathways and scenarios assessed in this study.

SI measure (SI)	Reference scenario (S0)	SI scenario (S1)
Consumption-side measure		
SI1. Changing human diet	Current diet based on FAO food balance	Recommended diet based on national recommended dietary guidelines
Production-side measures		
SI2. Replacing carbon-intensive ingredients in conventional feed to low carbon-intensive alternatives	Soybean meal in conventional feed	(a) Dry and (b) wet feed produced from food waste
SI3. Replacing monoculture cropping by crop rotation with legumes	Monoculture cropping:	Crop rotation:
	Continuous monoculture wheat	Grain legume-wheat rotation
	Continuous monoculture maize	Grain legume-maize rotation
SI4. Incorporating crop residues in the field	Removal of crop residues for bioenergy production	Crop residue incorporation in the field

$$\text{Food supply} = \text{Production} + \text{Import–Export} + \text{Stock change} \tag{1}$$

$$\text{Food consumption} = \text{food supply} - \text{food losses (on farm and food industry)} \tag{2}$$

$$\text{Food intake} = \text{food consumption} - \text{food wastage (at retailer and household)} \tag{3}$$

Food intake was calculated by food commodity, distinguishing nine groups of food commodities: (1) cereals and starchy foods; (2) dairy products; (3) fruits; (4) legumes and pulses; (5) vegetables; (6) eggs and meat products; (7) vegetable oils; (8) animal fats; (9) leeway, i.e. sugar, stimulants (coffee and cocoa) and alcoholic beverages (beer and wine).

National recommended diets were taken from various sources (see Table A3 in Appendix A). For each country, diets were converted into food intake (g/person/day; Table A2 in Appendix A), based on conversion factors provided in each of the national recommended dietary guidelines. The leeway was assumed to be 300–400 kcal/person/day, based on Dutch recommendations (van Dooren and Kramer, 2012). Countries that do not or incompletely quantify their recommended diet were excluded from our analysis. These include Croatia, Cyprus, Czech Republic, Lithuania, Latvia, Luxembourg, Malta, Poland, Slovakia, and Slovenia.

The life cycle system boundary of changing human diet includes primary production and transport. GHG emissions from primary production (including land use change) up to the distribution center were taken from Audsley et al. (2009; see details in Table B1 in Appendix B). The transport stage distinguishes three geographic regions, namely, domestic, other European countries, and outside Europe. Domestically produced food commodities and commodities imported from Europe were assumed to be transported by light goods vehicles (LGV) and heavy goods vehicles (HGV), respectively (Michalsky and Hooda, 2015). Transport emissions of imported food commodities from outside Europe were calculated based on ship transport (see Tables B2, B3 in Appendix B). Trade data of food commodities between main origin and destination country were taken from Simoes and Hidalgo (2011) database.

2.1.2. Calculation of GHG emission savings

The GHG emission savings of SI1 at country level were calculated using the following equations:

$$ES_{SI1} = \left[\sum_{i=0}^{n} (FI_{S0,i} - FI_{S1,i}) \times (E_{p,i} + E_{t,i}) \right] \tag{4}$$

$$E_{p,i} = I_{e,i} \times EF_e \tag{5}$$

$$E_{t,i} = Q_i \times D_{tm} \times EF_{tm} \tag{6}$$

where ES_{SI1} is the total GHG emission savings from changing human diet (g CO_2-eq/person/day); FI_{S0}, FI_{S1} is the food intake of food commodity i in the current human diet (S0) and recommended national diet (S1), respectively (kg/person/day); $E_{p,i}$ is the GHG emission from primary production (including land use change) of food commodity i (g CO_2-eq/kg food commodity); $E_{t,i}$ is the transport emission of food commodity i (g CO_2-eq/kg food commodity). $I_{e,i}$ is the energy input for the production of food commodity i and EF_e is the emission factor of the energy used. Q_i is the quantity of food commodity i- transported; D_{tm} is the distance travelled; EF_{tm} is the emission factor of specific transport mode used.

Distances between importing and exporting countries were defined by geographical positions of capital cities. For sea transport, the distance between the harbor of exporting countries and Rotterdam harbor in the Netherlands was established using the sea-distance.org (2018) web-based calculator. For road transport, distance was calculated using google maps.

2.1.3. Calculation of land use savings

Land use savings take into account food losses and wastage from post-harvest to consumers. These were calculated at country level as follows:

for food crop commodities:

$$LUS_{SI1a} = \frac{[(\Sigma\, Q_{S1,i}/Y_i) - (\Sigma\, Q_{S0,i}/Y_i)]}{P} \tag{7}$$

where LUS_{SI1a} represents the land use savings from changing human diet related to changes in food crops consumption (m^2/person/day); $Q_{S0,i}$, $Q_{S1,i}$ is the daily food intake of food commodity i in the current diet and recommended national diet, respectively (kg/day); Y_i is the average yield of food commodity i (kg/m^2); P is the population size of the country considered.

for animal products:

$$LUS_{SI1b} = \frac{\left[\sum_{t,i} \left(\frac{FD_t}{LW_t} \times Prop_{t,i} \times \frac{1}{yield} \times EA_i \right) \right]}{P} \tag{8}$$

where LUS_{SI1b} represents the land use savings from changing human diet related to changes in animal products consumption (m^2/person/day); FD_t is the daily feed demand required by livestock t (kg DM/day; see Eqs. (C1)–(C5) in Appendix C for detailed calculation); LW_t is the daily live weight gain of livestock t (kg/day); $Prop_{t,i}$ is the proportion of ingredient i (e.g. soymeal, grains, grass, fodder) in animal feed, on a dry matter basis (taken from Herrero et al., 2013); 1 / *yield* is the area (in m^2) required to produce 1 kg of raw product. This also includes grassland for ruminants. EA_i is the economic allocation factor for the proportion of the land required to produced ingredient i (e.g. soymeal from soybean), rather than to other co-products; P is the population size of the country considered.

2.2. SI2: replacing soybean meal in conventional feed by food waste-based feed

2.2.1. Description, system boundary and life cycle inventory

The soybean meal content of conventional feed ranges between 1.31% (pig fattening) and 36.10% (poultry broiler starting) (FeedPrint, 2015). About 68% of conventional feed produced in the EU is for poultry (34%) and pig (34%) consumption (FEFAC, 2010). Since poultry conventional feed has a high soybean meal content (25–36%), we assumed that the soybean meal in this conventional feed will be replaced by feed produced from food waste.

The amount of food waste produced from four principal waste streams (households, manufacturing, food industry, and retail) was taken from the best available data compiled by European Commission (2010). We assumed that on average 39.2% of the food waste could be recycled as animal feed, following Zu Ermgassen et al. (2016). We evaluated two types of feed produced from food waste: dry and wet feed (processes defined below), adopted from Salemdeeb et al. (2017). We assumed that feed from food waste substitutes conventional feed by 1:1 on a dry matter basis (Zu Ermgassen et al., 2016; Salemdeeb et al., 2017). According to Kwak and Kang (2006), replacing a conventional corn-soy diet with food waste mixtures did not have negative effects on pig production, carcass characteristics and meat quality. Therefore, the nutritious value of food waste mixture feed was assumed similar to conventional feed with soybean meal.

The life cycle system boundary of soybean meal in conventional feed (SBM-CF) and feed produced from food waste are presented in Fig. 1. The FeedPrint model (FeedPrint, 2015) was used to estimate GHG emissions of soybean meal in conventional feed produced in the EU. This includes crop cultivation, processing of soybean meal, processing of conventional feed, transportation, and crop specific emissions from Land use and Land use change (LULUC). We adopted the parameters used in the FeedPrint (2015) model (see Table B4 in Appendix B).

The potential GHG emissions of collection and transport of food waste in trucks were adopted from Manfredi et al. (2015). The GHG emissions of processing and transporting dry and wet feed produced from food waste were based on Salemdeeb et al. (2017) and Vellinga et al., 2013. The life cycle inventory data is presented in Table B4 in Appendix B.

However, replacing SBM-CF by feed produced from food waste is likely to result in trade-offs in the energy sector. Food waste can, theoretically, be utilized for energy production (Monforti-Ferrario et al., 2015), meaning that processing food waste into feed will reduce feedstock availability for bioenergy production. This reduction of feedstocks is assumed to be compensated by utilization of fossil fuels for electricity production, leading to additional GHG emissions. The electricity generated from food waste using anaerobic digestion is 260 kWh/t food waste (Salemdeeb et al., 2017).

2.2.2. Calculation of GHG emission savings

The GHG emission savings of SI2 scenario at country level were calculated as follows:

$$ES_{SI2} = \left(\frac{(GHG_{SCF}) - (GHG_{FWF} \times SF \times Q_{SCF})}{P}\right) + \left(\frac{AE_{CH_4} \times EF_{CH_4}}{P}\right) \tag{9}$$

where ES_{SI2} represents the GHG emission savings from replacing SBM-CF by food waste based feed (g CO_2-eq/person/day); GHG_{SCF} is the GHG emission from cultivation (including land use change) of soybean, taking into account the economic allocation factor of soybean meal of 0.361; soybean meal processing, conventional feed processing, and transport emissions of SBM-CF (g CO_2-eq/t SBM-CF, fresh weight). GHG_{FWF} is the GHG emission from food waste collection and transport, processing, and transport of feed from food wastes (g CO_2-eq/t feed, fresh weight); SF is the substitution factor for replacing SBM-CF by dry feed (0.9231 t SBM-CF/t dry feed) or wet feed (0.3721 t SBM-CF/t wet feed), adopted from Salemdeeb et al. (2017); Q_{SCF} is the quantity of SBM-CF being replaced by dry or wet feed (t/day); AE_{CH4} is the avoided methane emissions from diverting food waste- from landfill disposal (see Eq. (C6) in Appendix C for methane emissions calculation); EF_{CH4} is the CO_2-eq of methane. P is the population size of the country considered.

The additional GHG emissions in the energy sector are calculated as follows:

$$AE_{SI2} = \frac{(Q_{FW} \times G_e \times EF_e) + (AE_{CH_4} \times EF_{CH_4})}{P} \tag{10}$$

where AE_{SI2} represents the additional GHG emissions in the energy sector (g CO_2-eq/person/day); Q_{FW} is the average weight of food waste produced in t/day; G_e is the electricity generated from food waste (260 kWh/t) (Salemdeeb et al., 2017); EF_e is the CO_2 equivalent of electricity generation (541 g CO_2-eq/kWh; BioGrace, 2014); AE_{CH4} is the avoided methane emissions from diverting food wastes from landfill disposal (see Eq. (C6) in Appendix C for methane emissions calculation); EF_{CH4} is the CO_2-eq of methane. P is the population size of the country considered.

2.2.3. Calculation of land use savings

Land use savings at country level were calculated as:

$$LUS_{SI2} = \frac{\left(\frac{Q_{SM}}{Y_{SB}}\right) \times CF}{P} \tag{11}$$

where LUS_{SI2} represents the land use savings from this measure (m^2/person/day); Q_{SM} is the quantity of soybean meal replaced by feed produced from food waste (t); CF is the conversion factor of soybean meal to soybean (0.771); Y_{SB} is the yield of soybean in t/m^2/day; P is the population size of the country considered.

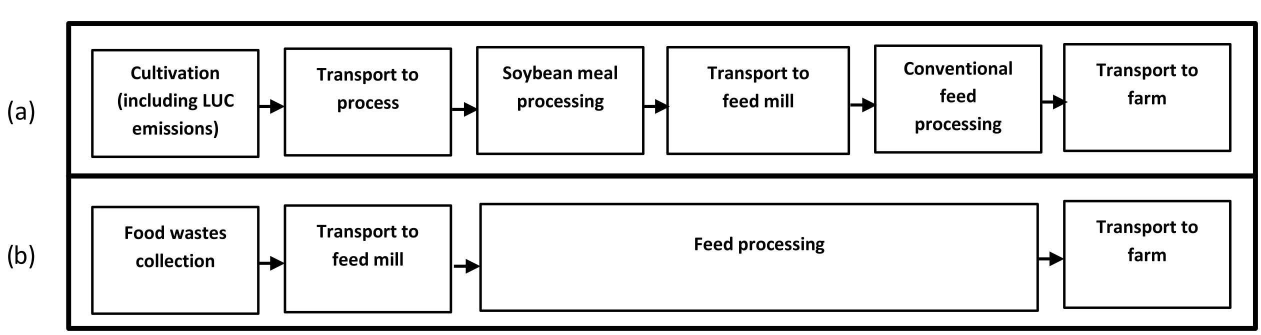

Fig. 1. Life cycle system boundary of: (a) soybean meal in conventional feed; (b) feed produced from food waste.

2.3. SI3: replacing monoculture cropping by crop rotation with legumes

2.3.1. Description, system boundary and life cycle inventory

We focused our analysis on rain-fed wheat and rain-fed maize because of their importance for global food production and food security. Wheat and maize account for approximately 66% of the EU-28 cereal production (Eurostat, 2016) but their yields are significantly suppressed, especially in Mediterranean and Eastern regions due to limited water, soil erosion and nutrient availability (Scherer et al., 2018). The production system of wheat and maize in the EU is dominantly based on monoculture cropping (GYGA, 2017). Reintegration of legumes into these cropping systems could reduce nutrient deficits and at the same time reduce GHG emissions.

We assumed that SOC changes related to legume production are insignificant (Monteleone et al., 2015). However, we took into consideration the interactions of legume production with the next crops (i.e. wheat and maize) in the rotation in terms of reduced fertilizer and pesticide application and Nitrous oxide (N_2O) emissions.

Crop rotation with legumes will result in the reduction of wheat and maize harvest. This reduction could trigger an increased production in major exporting countries, e.g. USA, Russia, and Brazil (FAOSTAT, 2010). At the same time, the increased production of legumes in the EU could decrease the import of soybeans and soybean meals from Brazil and Argentina, because legumes like peas and faba beans are relevant alternatives to soybeans in the European cropping systems and livestock diets (Knudsen et al., 2014). However, the reduction of soybean meal import to the EU also implies that a certain amount of soybean oil is not produced. A lower soybean oil production in Brazil and Argentina will presumably increase the production and import of palm, canola, sunflower, or other vegetable oil. We have included the overall climate impact of these changes in the GHG emission saving potential of crop rotation with legumes in the EU (see Eq. 12), data taken from Knudsen et al. (2014) and FeedPrint (2015) (Table B5 in Appendix B).

The main system boundaries include two main processes: 1) production of agricultural inputs; and 2) the agricultural production itself. The life cycle inventory in replacing continuous monoculture of wheat/maize by crop rotation with legumes is presented in Table B5 in Appendix B. The changes on yield, N-fertilizer input and N_2O emissions across the aggregated environmental zones (Atlantic, Boreal, Continental, Mediterranean, Nemoral; Lehtinen et al., 2014) were adopted from various sources (see Tables B5, B6 in Appendix B).

2.3.2. Calculation of GHG emission savings

The GHG emission savings of SI3 were estimated using the following equation:

$$\mathrm{ES_{SI3}} = \left(\frac{[((EI_{S0} - EI_{S1}) \times EF_{EI}) + ((NF_{S0} - NF_{S1}) \times EF_{EI})] \times AH}{P}\right) + \left(\frac{(E_{RP} + AE_{RP}) \times AH}{P}\right) \tag{12}$$

where $\mathrm{ES_{SI3}}$ represents the GHG emission savings from crop rotation with legumes as compared to continuous monoculture of wheat or maize (kg CO_2-eq/person/day); $\mathrm{EI_{S1}}$ and $\mathrm{EI_{S0}}$ are the energy inputs from cultivation in the SI scenario and the reference scenario, respectively (MJ/ha/day); $\mathrm{EF_{EI}}$ is the emission factor of specific energy utilized from cultivation (kg CO_2-eq/MJ); $\mathrm{NF_{S0}}$ and $\mathrm{NF_{S1}}$ are N-fertilizer inputs in the crop rotation and mono-cropping scenarios, respectively (kg N/ha); $\mathrm{EF_{NI}}$ is the emission factor of N-fertilizer (kg CO_2-eq/kg N); $\mathrm{E_{RP}}$ and $\mathrm{AE_{RP}}$ are the GHG emissions and avoided GHG emissions as a result of reduced wheat/maize production due to crop rotation, or the compensation for reduced grain due to crop rotation (see Eqs. (C7), (C8) in Appendix C); AH is the harvested area (ha); P is the population size of the country considered.

2.3.3. Calculation of land use savings

The potential land use savings at country level were calculated as follows:

$$LUS_{SI3} = \frac{\left(Y_{Saved} \times \frac{1}{Y_{S0}} \times AH\right)}{P} \tag{13}$$

where $\mathrm{LUS_{SI3}}$ represents the land use savings from replacing monocultures by crop rotations, in m^2/person/day. $\mathrm{Y_{Saved}}$ is the yield saved in g/m^2/day, and $\mathrm{Y_{S0}}$ is the baseline yield in g/m^2/day. AH is the harvested area (m^2); and P is the total population.

2.4. SI4: incorporating crop residues in the field

2.4.1. Description, system boundary and life cycle inventory

We focused our analysis on wheat straw and maize stover incorporation in the field (also called soil mulching). Crop residue quantities are estimated from harvest indices (i.e. the ratio of harvested grain to total shoot dry matter), using 1.0 in Western Europe and 1.5 in Eastern Europe for wheat, and 1.2 in Western Europe and 1.9 in Eastern Europe for maize (Krausmann et al., 2008). According to Gurría et al. (2017), one-third of the collected crop residues is used for animal feed and bedding and for horticulture purposes, while the other two-thirds are used in downstream sectors, including bio-materials and bioenergy. It is unknown how these two-thirds are split over bio-materials and bioenergy uses. In the reference scenario, we, arbitrarily, assumed that 67% of the collected crop residues were utilized for bioenergy production. The energy as electricity attainable from the combustion of straw is 5.4 GJ/t DM, assuming a 30% conversion efficiency (Yanga et al., 2007; Powlson et al., 2008).

In the SI scenario, 67% of the crop residues were assumed left on the soil surface after harvesting. We assessed the effect of crop residue incorporation in the field on SOC content and wheat and maize yield based on data from various experiments performed in Europe (Tables B7–B10 in Appendix B). Carbon accumulated in the soil might be regarded as C "saved", i.e. not emitted to the atmosphere as CO_2 (Powlson et al., 2008). We also considered the effects on N_2O emission. N_2O is formed during nitrification and denitrification, among others due to agricultural activities such as N fertilization (Don et al., 2012, Reiter, 2015). Reduced N-fertilization due to crop residue incorporation in the field might be regarded as GHG emission savings.

The main system boundaries include two main production stages: 1) The farm stage comprises cereal cultivation (applied both in the reference and alternative scenarios) and straw/stover chopping (only applied in the alternative scenario); and 2) the post-farm stage includes straw baling and transport (only applied in the reference scenario). In both the reference and the alternative scenarios, wheat and cereals were assumed cultivated in a conventional cropping system (i.e. conventional tillage) and in single-crop farming. The GHG emissions from cultivation, straw chopping, baling and transport were based from Monteleone et al. (2015) (Table B7 in Appendix B). Data about the SOC accumulation rate and changes in N_2O emissions and cereal yield due to straw incorporation in different agro-climatic zones were taken from various experimental studies in Europe (Tables B7–B11 in Appendix B).

A potential trade-off of incorporating crop residues in the field is increased GHG emission in the energy sector, due to the reduction of feedstock availability for bioenergy production. We assume that this reduction of feedstock is compensated by utilization of fossil fuels for the production of electricity.

2.4.2. Calculation of GHG emission savings

The GHG emission savings of SI4 at country level were calculated as follows:

$$ES_{SI4} = \frac{\left[(E_{S0} - E_{S1}) + ((NF_{S0} - NF_{S1}) \times E_{NF}) + \left(SOC_{AR} \times \frac{44}{12} \times Q_{CR}\right)\right] \times AH}{P} \quad (14)$$

where ES_{SI4} represents the GHG emission savings from this measure ($GHGS_{SI4}$; kg CO_2-eq/person/day); E_{S0} is the GHG emission from straw baling and transportation in the reference scenario; E_{S1} is the GHG emission from straw chopping in the SI scenario; NF_{S1}, NF_{S0} are N-fertilizer inputs in the scenarios with and without straw mulching, respectively (kg N/ha); E_{NF} is the GHG emission equivalent of N-fertilizer input (both production and use; kg CO_2-eq/kg N); SOC_{AR} is the SOC accumulation rate (kg C/ha/day) which is converted to CO_2 equivalents by multiplying with 44/12; Q_{CR} is the amount of crop residue applied (t/ha); AH is the harvested area maize or wheat in ha; and *P* is the total population.

The additional GHG emissions in the energy sector due to loss of feedstock for bioenergy production were calculated as follows:

$$AE_{SI4} = \frac{Q_s \times G_e \times E_e \times AH}{P} \quad (15)$$

where AE_{SI4} represents the additional GHG emission in the energy sector (kg CO_2-eq/person/day); Q_s is the quantity of crop residues incorporated, and, consequently, lost for bioenergy production (t/ha/day); G_e is the electricity generation from crop residues (kWh/t straw); E_e is the GHG emission of electricity production (0.541 kg CO_2-eq/kWh); AH is the harvested area (ha); and *P* is the total population.

2.4.3. Calculation of land use savings

Land use savings upon incorporating crop residues at country level were calculated as follows:

$$LUS_{SI4} = \frac{\left(Y_{Saved} \times \frac{1}{Y_{S0}} \times AH\right)}{P} \quad (16)$$

where LUS_{SI4} represents the land use savings from this measure (m^2/person/day). Y_{Saved} is the yield saved (kg/ha/day) and Y_{S0} is the baseline yield; AH is the harvested area (ha); and *P* is the total population.

2.5. Sensitivity analysis

Our study makes many assumptions on e.g. transport mode, cultivation practices, allocation factors and technology used. These assumptions render a certain degree of uncertainty. The parameters that we applied from experimental studies have related uncertainties as well. These factors do play a major role in the GHG impacts of different SI measures. To assess the uncertainty in this study, we performed a sensitivity analysis (Table 2). The life cycle inventory for sensitivity analysis is presented in Appendix D.

We focused on specific assumptions (see Table 2) because of their importance for GHG emissions. Transportation has a significant impact within the food and beverage sector because of the common long shipping distances (Knudsen et al., 2011). Air transport is considered as an alternative in the sensitivity analysis because this is also the most important means of long-distance transport. Allocation issues arise in life cycle based environmental accounting when a system produces multiple product outputs (Allacker et al., 2014). The production of soybean meal and soybean oil involves co-product relationships that require allocation decisions. The two allocation factors commonly used in LCA are mass and economic allocations. Tillage practices have been observed to influence SOC concentration, yield and N_2O emissions (Lehtinen et al., 2014; Liu et al., 2014).

3. Results

3.1. GHG emission savings

The average GHG emission savings of shifting from the current human diet to the recommended national diets in the EU is 1872 g CO_2-eq/person/day. Highest GHG emission savings are seen in Austria and Denmark, lowest in Spain and Estonia (Table 3). More than half of the GHG emission savings in this SI measure are savings of embodied GHG emissions, or reduced GHG emissions due to reduction of imported commodities (Fig. E1 in Appendix E), with considerable savings from reduced imports from South America (91%) (Fig. 3). Transport emissions of imported food commodities contribute about 10% to the total GHG emissions from food production and transport.

Compared to changing human diet, supply-side measures can only marginally to moderately contribute to GHG savings (Table 3). Replacing imported soybean meal in conventional feed by food waste-based feed can save on average between 77 (dry feed) and 89 (wet feed) g CO_2-eq/person/day, with highest potential savings in the Netherlands and lowest potential savings in Greece (Table 3). These GHG savings exclusively originate from embodied GHG emissions, because soybean meal was assumed imported from South America. Introducing rotations with legumes in wheat or maize monocultures (with conventional tillage) results in an average saving of 71 g CO_2-eq/person/day, ranging between -5 g CO_2-eq/person/day (Cyprus) and 260 g CO_2-eq/person/day (Hungary) (Table 3). Incorporating crop residues into the soil instead of removal for bioenergy production could save between 1 g CO_2-eq/person/day (Portugal and Cyprus) and 413 g CO_2-eq/person/day (Hungary). Altogether, the largest GHG savings through supply-side measures are possible in Hungary, but these still only comprise 39–53% of the savings possible through dietary change in that country.

Introducing rotations with legumes in wheat or maize monocultures

Table 2
Description of the scenarios for the assessment of the uncertainty in different SI measures assessed in this study.

SI measure	Reference scenario	Sensitivity analysis
SI1: Changing human diet	Food commodities imported outside Europe are transported by ship	Food commodities imported outside Europe are transported by aircraft
SI2: Replacing soybean meal in conventional feed by feed produced from food wastes	Soybean meal economic allocation Feed from food waste substitutes conventional feed by 1:1 on a dry matter basis	Soybean meal mass allocation Substituting of conventional feed based on the ratio between crude protein of food wastes[a] and soybean meal[b] o minimum: 19.8/43 = 0.460 o maximum: 25.8/49 = 0.526
SI3: Replacing cereal monoculture by legume-cereal rotation	Crops are cultivated according to conventional tillage	Crops are cultivated according to conservation tillage (no-till)
SI4: Incorporating crop residues in the field	Crops are cultivated according to conventional tillage	Crops are cultivated according to conservation tillage (no-till)

[a] Sayeki et al. (2001).
[b] Heuzé et al. (2017).

Table 3
GHG emission savings from changing human diet and replacing livestock diet scenarios in the EU.

Country	GHG emission savings (g CO_2-eq/person/day)				
	Consumption-side measure	Production-side measure			
	Changing human diet (SI1)	Replacing soymeal based feed by food waste feed (SI2)		Monoculture to crop rotation (SI3) (conventional tillage)	Incorporating crop residues in the field (SI4) (conventional tillage)
		Wet feed	Dry feed		
Austria	2570	114	95	62	80
Belgium	2432	197	165	34	60
Bulgaria	1219	47	39	155	143
Croatia	ND	ND	ND	166	321
Cyprus	ND	119	99	5	1
Czech Republic	ND	36	30	71	107
Denmark	2463	60	50	122	151
Estonia	901	138	115	76	56
Finland	1776	97	81	44	23
France	2230	74	62	91	118
Germany	1380	66	56	40	57
Greece	2038	23	19	40	15
Hungary	1702	95	80	260	413
Ireland	1911	117	98	21	33
Italy	2026	76	63	20	11
Latvia	ND	54	45	82	81
Lithuania	ND	96	80	129	134
Luxemburg	ND	97	81	32	32
Malta	ND	33	27	ND	ND
Netherlands	2066	293	245	9	14
Poland	ND	120	100	52	61
Portugal	1677	68	57	12	1
Romania	1834	58	48	219	210
Slovakia	ND	56	47	88	112
Slovenia	ND	45	37	53	109
Spain	516	85	71	28	10
Sweden	2096	113	94	38	41
UK	2222	118	99	30	41
EU-28 (g CO_2-eq/person/day)	1872	89	77	71	87
EU-28 (kt CO_2-eq/year)	283257	16771	14042	10682	12,701

ND - no data/incomplete data.

and incorporating crop residues in the field has a potential to increased GHG emission savings by > 36% in case no-till management practice are implemented (Tables 3 and E1 in Appendix E). However, these increased GHG emission savings of combined no-till and crop rotation or crop residue incorporation in the soil relative to conventional tillage are likely to lead to a reduction of wheat and maize yield (Pittelkow et al., 2015a, 2015b). No-till could thus reduce the effectiveness of crop residue incorporation and crop rotation with legumes in reducing yield gaps (Tables E2, E3).

The figures in Table 3 show that changing from current diet to a national recommended diet has the greatest potential for carbon mitigation, but even this can only account for only < 6% of total anthropogenic CO_2-carbon produced in the EU-28. At country level, the highest reduction is found in Romania and Sweden (> 10%) and the lowest reduction in Estonia and Spain (< 3%) (Fig. 4). Combining the production-side SI measures could only contribute to 1% reduction of the total anthropogenic CO_2 in the EU, with highest contribution in Hungary (4%) (Fig. 4).

3.2. Land use savings

The average land use savings of shifting from current human diet to national recommended diet is 3.32 m^2/person/day, with highest savings per capita in Greece (7.63 m^2/person/day) and lowest in Hungary (1.60 m^2/person/day; Table 4). About 85% of the land savings in Greece and Italy concerns domestic arable land and grasslands (Fig. 5). Replacing soybean meal by food waste in livestock feed would reduce the area of soybean required in South America by 1.12–1.49 Mha/year, depending on the use of dry or wet feed (Table 4). Replacing monoculture cropping by crop rotations and incorporation of crop residues into the soil have a considerable potential to reduce land required for wheat and maize production by increasing their yield. Nevertheless, overall land savings that can potentially be achieved from supply side measures are only 14% of land savings from changing diets. Only in Hungary, Bulgaria, and Romania, land savings from supply side measures are more than one-fifth of land savings from dietary change.

Shifting from monoculture cropping to crop rotation with legumes (in conventional tillage) could reduce yield gaps of rain-fed wheat by 1% (in Portugal) to 36% (in the Netherlands) and rain-fed maize by 8% (in Poland) to 54% (in Austria) (Tables E3, E4). Incorporating straw into the soil (in conventional tillage) could reduce yield gap of rain-fed wheat by 4% (in Portugal) to 39% (in Netherlands) and rain-fed maize by 6% (in Poland) and 59% (in Germany) (Tables E3, E4). However, no-till resulted a negative impact on yield, it reduced the benefits of crop rotation with legumes and incorporating crop residues in the soil in reducing yield gap especially in temperate regions. In Mediterranean regions, the effect of no-till on yield is positive (Tables E3, E4).

3.3. Trade-offs with bioenergy production as a climate change mitigation strategy

Although supply-side measures can contribute to GHG emission- and land use savings, using crop residues and food waste for bioenergy production could contribute more to climate change mitigation. Fossil fuel emissions avoided when food waste would be used for electricity generation (16 Mt CO_2-eq/year) exceed the emission reduction achieved when food waste is used to produce dry feed (14 Mt CO_2-eq/year) (Fig. E3 in Appendix E) at EU level. Using straw for combustion to generate electricity has the potential to save 4–8 times more CO_2 than incorporating straw in the soil to increase SOC level (Fig. E2 in Appendix E). Only the use of food waste for the production of wet feed is a more efficient strategy in terms of GHG emission than using the biomass for energy generation, with 5–14% of exceedance (Fig. E3).

3.4. Sensitivity analysis

The results of the sensitivity analysis imply that there is high sensitivity to mode of transport. When commodities would be transported by air, transport emissions would comprise up to 80% of the total emissions instead of the 10% comprised by sea transport. GHG emission savings increased by 62% when full air transport has been implemented relative to assumed full sea transport. With regard to the allocation factor for assessing the soybean meal carbon footprint, there is only 10% difference on the GHG emission savings between applying economic and mass allocation factors. The GHG emission savings of modifying protein ratios between feed produced from food wastes and conventional feed with soybean meal is 22% lower compared to applying 1:1 ratio (dry matter content). The GHG savings of combined no-till and crop rotation or crop residue incorporation in the soil is > 36% higher relative to conventional tillage.

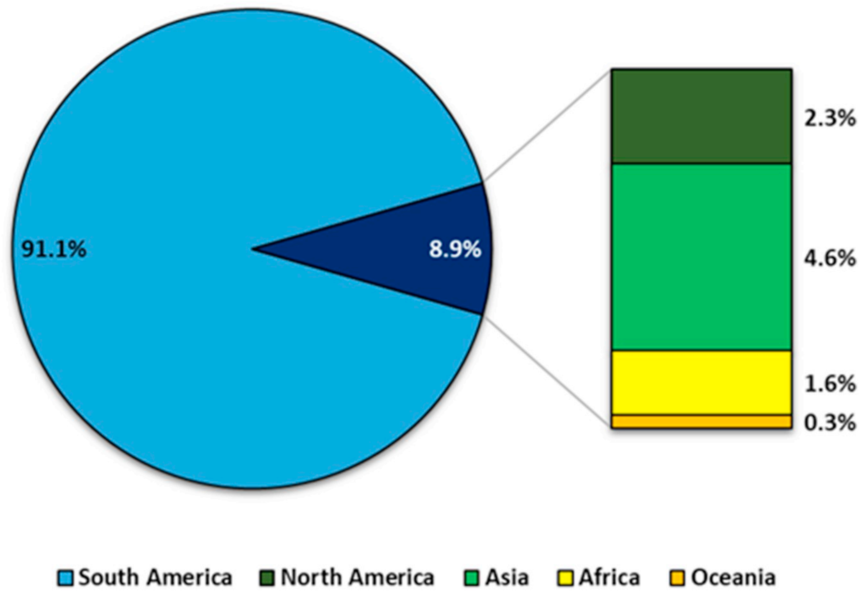

Fig. 2. Share of embodied GHG emission savings due to reduction of imported commodities at global continents in the changing human diet scenario in the EU.

4. Discussion

4.1. Comparison with other studies

We compared our estimated GHG emission savings and land use savings from changing current diet to a national recommended diet with studies by van Dooren et al. (2014) and Meier and Christen (2013), who focused on the Netherlands and Germany only. While we estimate GHG emission savings at 2.07 kg CO_2-eq/person/day and land savings at 2.3 m^2/person/day in the Netherlands and at 1.38 kg CO_2-eq/person/day and 2.80 m^2/person/day in Germany, these comparison studies found GHG savings of 0.5 kg CO_2-eq/person/day and land savings of 2.1 m^2/person/day in the Netherlands and at 0.63 kg CO_2-eq/person/day and 0.99 m^2/person/day in Germany. The difference is mainly due to the exclusion of transport emissions, as well as foods and beverages such as beer, wine, coffee, tea and cocoa in the analyses by van Dooren et al. (2014) and Meier and Christen (2013). As the nationally recommended diets advise a strong reduction in leeway consumption, these food groups have a significant effect on GHG emissions and savings. The differences on methods used, source and reference year (2010 vs 1998 and 2006) of current intake as well as the GHG emission factors used also contribute to different results.

The use of food waste as replacement for soybean meal in conventional feed of poultry in this study could potentially save 1.5 million ha of agricultural land. Zu Ermgassen et al. (2016) estimated a potential savings of 1.8 million ha of agricultural land by replacing EU pork conventional feed by feed from food waste. While estimated values are in the same order of magnitude, the lower value for our EU study is mainly due to differences of quantity and type of ingredients (e.g. soybean meal, cereal grains, etc.) in conventional feed assessed; in this study we only focused on soybean meal in conventional feed while Zu Ermgassen et al. (2016) also included other ingredients of conventional feed like cereal grains.

To our knowledge, no previous studies exist on the overall potential contribution of crop rotation with legumes and incorporation of crop residues in the field on GHG emissions and land use at EU level. We therefore compare the parameters (e.g. yield change, SOC accumulation rate, etc.) we applied to estimate the GHG emissions- and land use savings of these SI measures. We employed an average SOC accumulation rate of 47 kg C/ha/year/t crop residues fresh matter applied, taken from various experimental data in Europe (Table B10 in Appendix B). This supports the average value of 49 kg/ha/year/t fresh weight crop residues reported by Nicholson et al. (2014) in Europe, Australia and North America. At EU level, no till combined with other SI measures (i.e. crop rotation and crop residue incorporation in the soil) reduced wheat yield by 6% and 11% (this study) relative to conventional tillage. This is quite similar to the estimated value of Pittelkow et al. (2015a, 2015b) at global level where no-till reduced wheat yield by 3% and maize yield by 8%. The range of values reflects the range of experimental conditions, especially on soil type and management practices, climate and other external factors.

4.2. Potential benefits of different SI pathways

The assessed SI measures in the EU have potential to reduce GHG emissions and increase land use savings within and outside Europe. There is a considerably greater climate change mitigation potential through saved CO_2 emissions by shifting from current to recommended diet as compared to other SI measures (Table 2). However, alternative use of biomass residues renders a risk of displacement, that nullifies the GHG emission reduction (but may have large other benefits). Instead of increasing SOC stocks by incorporating crop residue in the field or replacing soybean meal in conventional feed, utilizing biomass residues for electricity generation to replace fossil fuels might be more efficient in terms of GHG emission savings and land savings. This agrees with the findings of Poeplau et al. (2015) and Powlson et al. (2008), who found in studies in Sweden and north-west Europe that replacing diesel by straw combustion to generate electricity saved 7 times more CO_2-equivalents than SOC accumulation by straw incorporation. Utilizing crop residues for bioenergy generation aligns with the EU's goal to increase the share of renewable energy from 9% (in 2010) to 30% of the total energy consumption by 2030 (European Commission, 2016). However, this contradicts the Common Agriculture Policy (CAP) 2014–2020 aim to maintain soil organic matter levels through Good Agriculture and Environmental Condition (GAEC) schemes (Council of the EU, 2009). Removing crop residues for energy production might contribute to further soil C depletion. This puts productivity at risk, particularly in Mediterranean countries and also parts of France, Germany, Poland, the Czech Republic and Slovakia, where low SOC concentrations are observed (de Brogniez et al., 2015).

Crop residue incorporation in the field also improves soil structure, reduces soil erosion and contributes to soil nutrient recycling (Poeplau et al., 2015), and can thus in multiple ways contribute considerably to GAEC measures. To achieve both policy goals, multiple sources of

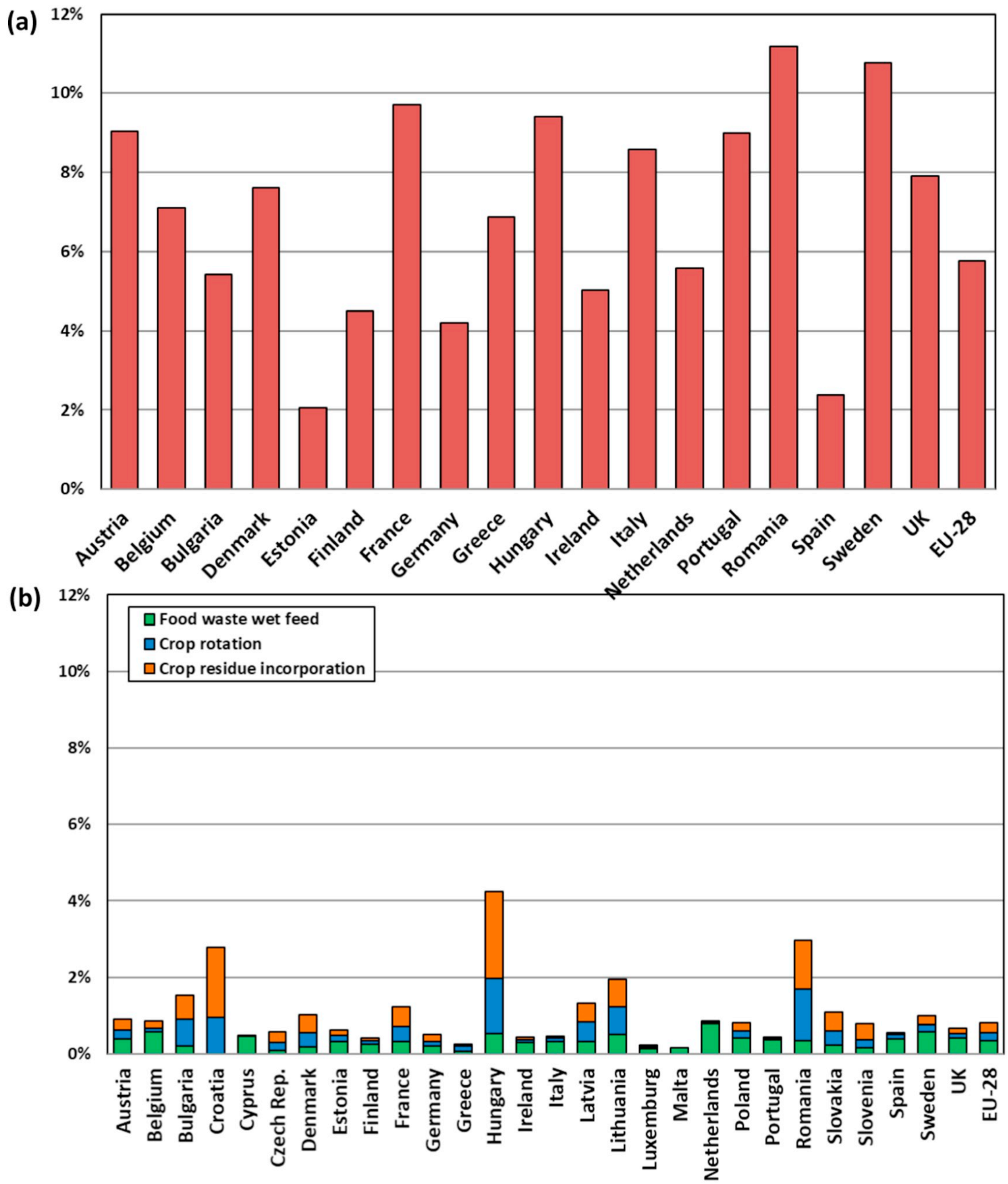

Fig. 3. Effect of (a) consumption-side measure (i.e. changing to a national recommended diet) and (b) production-side measures (i.e. food waste as feed, crop rotation, and crop residue incorporation) on total anthropogenic GHG emissions (i.e. GHG emissions from all sectors) in the EU-28.

biomass are required, that will lead to extra tradeoffs in terms of land use, greenhouse gas emission displacement, or environmental quality. Instead of using crop residues for bioenergy production, food waste is the best alternative. Given that food waste for feed production (especially dry feed) resulted to less GHG emission savings as compared to utilizing food waste for bioenergy production.

Changing human diet not only contributes to land and GHG savings in Europe, but also elsewhere. The total land use saving is equivalent to 44% of the arable land and permanent crops in the EU. This increased land use efficiency enhances availability of land for other uses, including energy crops for bioenergy production, and enables to set aside and protect larger areas of forest and other natural ecosystems (Edwards et al., 2015). Alternatively, more efficient land use in regions where expected effects are largest, can allow for reducing intensification elsewhere. This can contribute to maintaining threatened cultural landscapes (Tieskens et al., 2017), that might have an important role in local economic and social sustainability. Crop residue incorporation in the field and crop rotation with legumes practices can contribute to closing yield gaps (Tables E2, E3 in Appendix E). An increase in quality and quantity of SOM could improve the soil productivity (Lal, 2004) leading to increase crop yield. Legume break crops in crop rotation are reported to increase subsequent cereal yields by 15–25% (Kirkegaard et al., 2008). This yield benefit was mainly due to reduced crop failure from leaf and root disease incidence in the following cereal crop (Stevenson and van Kessel, 1997; Reckling et al., 2014). High diversification of the crop rotation also helps to reduce problems caused by weeds, pests and pathogens (Nemecek et al., 2008), and increases resilience to drought and climate change due to higher SOC (Song et al., 2015; Blanco-Canqui and Lal, 2009). Altogether, a full trade-off of the effects should not only consider the GHG emission displacement, but

Table 4
Land use savings (m^2/person/day) from different sustainable intensification (SI) measures in the EU member states (EU-28).

Country	Land use savings (m^2/person/day)				
	Changing human diet (SI1)	Replacing soybean meal by feed produced from food waste (SI2)		Replacing mono-cropping by crop rotation (SI3)	Incorporating crop residues in the field (SI4)
		Dry feed	Wet feed		
Austria	3.94	0.08	0.10	0.19	0.23
Belgium	2.87	0.13	0.18	0.07	0.13
Bulgaria	2.06	0.03	0.04	0.48	0.42
Croatia	ND	ND	ND	0.52	0.41
Cyprus	ND	0.08	0.11	0.01	0.01
Czech Republic	ND	0.02	0.03	0.22	0.19
Denmark	3.00	0.04	0.05	0.27	0.54
Estonia	2.80	0.09	0.12	0.15	0.16
Finland	2.00	0.07	0.09	0.09	0.09
France	3.64	0.05	0.07	0.20	0.43
Germany	2.80	0.04	0.06	0.11	0.17
Greece	7.63	ND	ND	0.05	0.04
Hungary	1.60	0.06	0.09	0.81	0.66
Ireland	2.78	0.08	0.11	0.05	0.09
Italy	5.05	0.05	0.07	0.03	0.02
Latvia	ND	0.04	0.05	0.16	0.17
Lithuania	ND	0.06	0.09	0.25	0.26
Luxemburg	ND	ND	ND	0.07	0.14
Malta	ND	ND	ND	ND	ND
Netherlands	2.30	0.20	0.26	0.02	0.04
Poland	ND	0.08	0.11	0.16	0.14
Portugal	4.00	0.05	0.06	0.02	0.03
Romania	2.95	0.04	0.05	0.68	0.55
Slovakia	ND	0.04	0.05	0.27	0.23
Slovenia	ND	0.03	0.04	0.17	0.13
Spain	2.53	0.06	0.08	0.04	0.08
Sweden	2.82	0.08	0.10	0.09	0.08
UK	3.11	0.08	0.11	0.07	0.13
EU-28 (m^2/person/day)	3.32	0.06	0.07	0.19	0.20
EU-28 (Mha/year)	53.42	1.12	1.49	2.72	3.53

ND - no data/incomplete data.

also the synergies with ecosystem service provision and climate change adaptation.

4.3. Challenges of implementation of different SI measures

Animal proteins play an important role in current European diets, while recommended national diets tend to suggest a decrease in animal protein consumption. The scope for drastic dietary changes in the EU seems to be limited. According to a survey among 13,500 participants in 13 European countries, many of the European consumers (95%) find it hard to imagine their diet without animal food products, especially cheese (ING International Survey, 2017). Animal products like cheese and milk are part of culinary culture in Europe, as demonstrated by the large share of cheeses in European Geographical labels (Tieskens et al., 2017). The strongest personal motivator for dietary change in the EU is the increasing evidence of the health benefits of a plant-based diet compared to an animal protein based diet (Hu, 2003; Springmann et al., 2016). However, the lack of knowledge of the negative effects of consuming high amounts of animal food products, culinary culture and traditions, rising incomes and lack of financial incentive to switch are the major reasons preventing people from lowering their consumption of animal proteins (ING International Survey, 2017). Recently, this is changing due to more widespread attention for the negative climate impacts of meat consumption and mainstreaming of vegetarian diets. Due to the difficult behavioral change required to change diets and due to increased affluence, worldwide, animal protein consumption shows an increasing trend (Kastner et al., 2012), suggesting that studies that address land savings and GHG savings upon a complete shift to plant-based diets (Scarborough et al., 2014; Springmann et al., 2016; Erb et al., 2016) provide a potential estimate of the savings rather than a realistically feasible estimate. Compared with other studies on changing human diets, assessing the potential of national recommended diets has the advantage of showing the large benefits of even more modest changes in diet.

A limitation regarding feed production from food waste is the limited availability of suitable food waste. Avoiding food loss and waste along the full supply chain from harvest to consumer is, currently, the most favored options under the EU Waste Framework Directive (European Commission, 2008). Moreover, the use of food waste for animal feed is not yet widely accepted in the EU (European Commission, 2002). Because especially wet feed has a large GHG emission saving potential, efforts to promote the inclusion of food waste

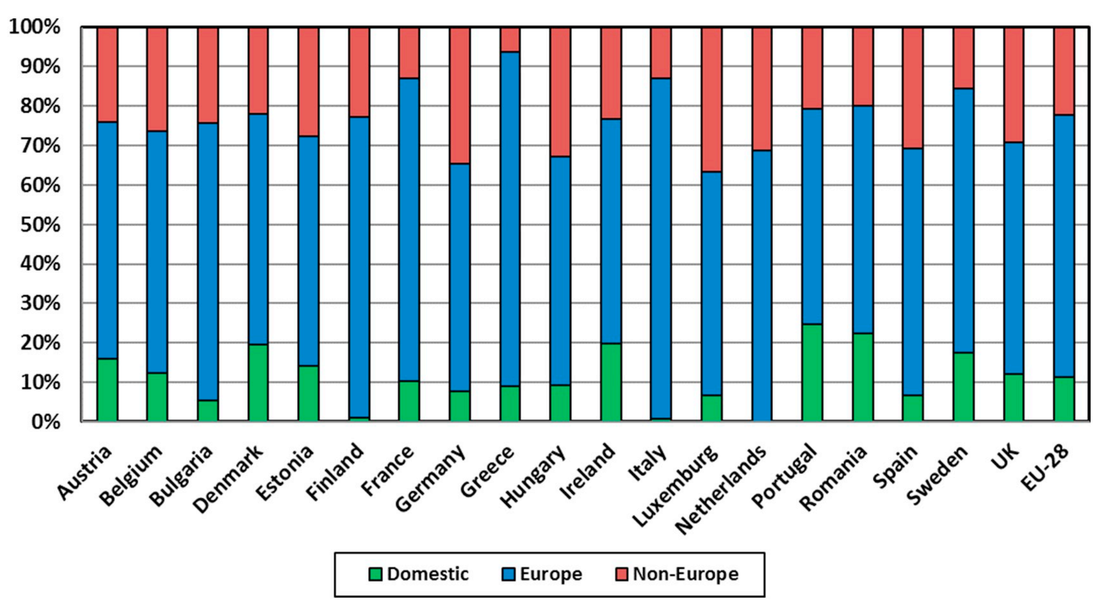

Fig. 4. Percentage of land use savings attributed to domestic production and imports of food commodities in the changing human diet scenario.

in animal feed should be supported by EU policy.

Crop residue incorporation in the field is limited by the availability of residues, and competing use for ruminant feed or as biofuel. In most EU countries, only during the winter or on agricultural land with significant slope soil cover is required (Council of the EU, 2009) and no member state has rules on a minimum amount of residue that should be left in the field. In contrast to other continents, the use of soil mulching in Europe is rather low (Searle and Bitnere, 2017; Prestele et al., 2018), suggesting on the one hand a large potential for uptake, but on the other hand pointing to resistance to this strategy.

4.4. Uncertainties and limitations of the study

This study is based on a set of relatively straightforward calculations, that quantify logical but strong assumptions with related uncertainties. The sensitivity analysis quantified the impacts of the major uncertainties in the analysis as well as the range of influence of alternative assumptions on the final results. A prime uncertainty is the variability in the modes of transport, especially for goods imported from outside Europe. Our calculation of transport emissions from imported food assuming full sea transport was, as part of the sensitivity analysis, contrasted with the extreme alternative of full air transport, demonstrating a high sensitivity to mode of transport, with transport emissions varying up to a factor 3. Regardless of this large uncertainty, diet change provides the largest potential for GHG emission reduction among the options considered. The analysis on food waste for animal feed production is inevitably constrained by data availability, in particular by uncertainty about the quantity and quality of food waste produced in the EU at consumer or household level. By using best available data, focusing only on food waste produced by sectors other than households, and performing sensitivity analysis, we were able to provide the best estimate currently possible.

The limited available information on legume crop management and pre-crop effects on N-fertilizer input as well as the effects of crop residue incorporation in the field on SOC and N_2O emissions in Europe was the greatest challenge for the data collection and propagates uncertainty into the results. For example, we assumed a linear relationship between crop residue input and SOC accumulation (Thomsen and Christensen, 2004). However, this assumption might over-estimate the GHG emission savings of crop residue incorporation in the soil because the quantity of C that can be accumulated in any soil is finite; after a change of management practices, SOC content increases towards an equilibrium value and then stabilizes (Powlson et al., 2008). SOC is highly variable over space, and small changes over time compared to the SOC stock make SOC changes difficult to measure (Garcia-Oliva and Masera, 2004). Tillage or ploughing practices also may influence the impact of residue retention on SOC (Searle and Bitnere, 2017; Lehtinen et al., 2014; Pittelkow et al., 2015a, 2015b). Although no-till is less common in the EU at the moment (Eurostat, 2015), we considered the role of a synchronous shift to no-till cultivation as part of the sensitivity analysis. No-till combined with crop rotation or crop residue incorporation increased GHG emission savings by > 36% compared to reference scenario. This large impact stresses the relevance of this measure, but trades off with a higher yield gap, requiring more land for the same wheat and maize production. Besides the effect of management practices, the efficiency of incorporating crop residues to increase SOC stocks is affected by the quality of the substrate Lal (2004), and soil texture (Poeplau et al., 2015; Powlson et al., 2012). We did not consider the effects of substrate quality on SOC because of limited data. We did not differentiate between soil types because we find no significant relationship between clay content and changes on SOC in our data.

5. Conclusions

The sustainable intensification measures assessed in this study have the potential to reduce GHG emissions and increase land use efficiency in the European agriculture sector as well as outside Europe. Among these SI options, shifting from current diets to national recommended diets showed by far the highest potential, about 283–468 Mt CO_2-eq/year of GHG emission savings. These GHG savings are 9 to 16 times larger than GHG savings of combined supply-side SI measures taken in the agricultural sector. Additionally, the assessed dietary changes allow for 53 Mha/year of land use savings.

Our study confirms other studies that dietary changes has a significant potential to mitigate climate change while the benefits of other SI measures are unlikely to be able to keep up with increasing consumption. However, we acknowledge their importance with regards to their potential to improve soil physical properties and resilience to drought due to higher SOC. Insight in the respective contributions as provided in this study is very important for properly targeting investments for implementation of the most effective and priority SI measure and identifying their potential trade-offs.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2018.11.042.

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